Environmental Health Perspectives
Vol. 91, pp. 45–48, 1991

Radiation Dosimetry

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This article summarizes the basic facts about the measurement of ionizing radiation, usually referred to as radiation dosimetry. The article defines the common radiation quantities and units; gives typical levels of natural radiation and medical exposures; and describes the most important biological effects of radiation and the methods used to measure radiation. Finally, a proposal is made for a new radiation risk unit to make radiation risks more understandable to nonspecialists.

Definition of Ionizing Radiation

Ionizing radiation includes any electromagnetic or particle radiation with sufficient energy to ionize common molecules. In this article I will consider only the electromagnetic component, specifically X-rays and gamma rays, encountered in the medical area.

Radiation Quantities and Units

The evolution of terminology in radiation dosimetry finds us in a state of transition. We are going from old units, which have been used for many decades, to new units based on SI (International System) units. Since both sets of units are encountered in the literature, it is necessary to have an understanding of both sets. The basic radiation quantities are exposure, dose (or absorbed dose), and dose equivalent (and its related quantity "effective dose equivalent").

Exposure = Ionization in Air

The old unit to measure exposure is roentgen (R), which is defined in terms of the amount of ionization produced in air. The unit for exposure is based on charge/mass of air (C/kg), where 1 R = 2.58×10^{-4} C/kg. The new unit for exposure has no name and is given as C/kg. Exposure is only measured in air and does not apply to ionization by charged particles or by photons with energies above 3 million electron volts (MeV). The concept of exposure is gradually being replaced by "air kerma," which is not yet in common use and will not be defined.

Dose (or Absorbed Dose) = Energy/Mass

The old unit for dose or absorbed dose is the rad, where 1 rad = 100 ergs/g. It was convenient that 1 R of exposure would give a dose of about 1 rad in water or human soft tissue. The new unit of dose is the grey (Gy), where Gy = 1 J/kg, thus 1 Gy = 100 rad. You will sometimes see doses given in centigray (cGy) which, of course, is a way to beat the switch to the SI system and still think in rad. Dose is based on energy/mass, but the very small energies encountered in measurements are made using the ionization of air or other substances. The results are converted to energy/mass by calculation.

Dose Equivalent Includes Bioeffects of Radiation

The third important radiation quantity is the dose equivalent (H). H is not a measured quantity. It is defined as the dose times a quality factor (QF). QF takes into account the relative biological effectiveness (RBE) of the type of radiation being used. For photons and electrons (beta rays), QF is defined as 1.0. For a densely ionizing particle, such as an alpha particle, QF is 20. The RBE depends on the biological system studied, so that QF is at best an approximation. In the old units, H = rad × QF rem. In SI units, H = Gy × QF sieverts (Sv). Since 1 Gy = 100 rad, 1 Sv = 100 rem. Note that since QF is a numerical factor, the basic units of dose equivalent are the same as for dose, energy/mass. Also note that since QF is 1.0 for photons and electrons, the dose equivalent is numerically equal to the dose for nearly all medical radiations.

How Partial Body Doses Are Added: The Effective Dose Equivalent

Generally, the radiation dose to the body is not uniform. For example, the dose to the lungs from alpha particles originating from radon and its daughter products is much greater than the dose to the rest of the body from natural radiation. Also, medical X-rays are

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limited to a small part of the body. To take this nonuniformity into account, we use the concept of "effective dose equivalent." That is, the effective dose equivalent is the amount of radiation that would result in the same radiation risk if it had been given to the whole body.

Natural or Background Radiation Versus Medical Exposures

Since the beginning of the Earth, natural radiation from cosmic rays and natural radioactivity have been present. This is still the major source of radiation to the public. No measurable harm has been demonstrated because of this radiation. However, based on biological effects at much higher doses, it is possible to extrapolate to these low doses and predict a certain number of cancers from this cause. An alternate explanation is discussed in the next section.

The recent inclusion of the large natural dose to the lungs from radon and its daughter products has caused the average annual dose from background to increase by a factor of about three in recent years. It used to be given as about 1 mSv; now it is about 3.0 mSv. The average American receives about 0.3 mSv effective dose equivalent from medical exposures. The dose equivalent for common X-ray studies range from 0.03 mSv for dental X-ray to about 7 mSv for a barium enema (lower gastrointestinal) X-ray study. See Table 1 for a new way of looking at these values.

The Hormesis Effect: Is a Small Amount of Radiation Healthy?

Studies in nuclear workers often show that they have less cancer than other members of the population and even of other workers with similar jobs. This is usually explained as the healthy worker effect. That is, for reasons not understood, radiation work attracts healthy workers. An alternate explanation which is rarely mentioned is the possibility that a small amount of radiation is good for you. This is referred to as the "hormesis" effect. Since humans and all of our ancestors evolved in a sea of natural radiation, it is possible that mutations have occurred that produce the hormesis effect. Animal experiments have demonstrated the hormesis effect. Rats exposed to increased radiation have a longer survival than their controls.

Table 1. Typical values of radiation risk.

Study	BERT[a]
X-Rays	
Dental	1 week
Chest	2 weeks
Skull	1 month
Thoracic spine	4 months
Lumbar spine	1 year
Barium meal	3 years
Barium enema	6 years
Nuclear medicine	
Vitamin B_{12} absorption	2 months
Red cell volume	4 months
Thyroid scan (^{99m}Tc)	8 months
Thyroid scan (^{131}I)	20 years
Kidney scan (^{99m}Tc)	1 year
Bone scan (^{99m}Tc)	2 years
Brain scan (^{99m}Tc)	3 years
Thyroid uptake (^{131}I)	30 years

[a] BERT, background equivalent radiation time.

Biological Effects of Radiation: Cancer, Mutations, and Birth Defects

The biological effects of ionizing radiation were not recognized until man-made X-rays were produced (*1*). The primary risks are carcinogenesis, mutagenesis, and teratogenesis; in other words, the possibility of inducing cancer, mutations, and birth defects. For diagnostic uses of radiation, the risk from carcinogenesis is the major concern. The probability of inducing a cancer depends on the amount of radiation energy absorbed by the body and the tissues that absorb the radiation. The energy absorbed by the tissues is usually of the order of 5 to 500 mJ. The carcinogenesis risk is greater for some tissues. For example, the blood-forming cells in the bone marrow are most sensitive for the induction of leukemia. Cancer is a very common disease, affecting about 25% of the population during their lifetime. The amount that is induced by ionizing radiation is not measurable but is generally believed to be very small. For example, studies on the survivors of the atomic weapons dropped on Hiroshima and Nagasaki found no increase in cancer in survivors with 0.1 Gy (10 rad) of whole body dose. All of our predictions of radiation risks at low levels are based on extrapolations of much larger doses. It is possible that the effects of radiation given at low dose rates are much less than from radiation given at the high dose rates used for most radiation research.

The Genetic Doubling Dose

The genetic effect of radiation has been known for about 50 years. Mutations occur for other reasons. It is estimated that it would require a dose to the gonads of about 2 Gy (200 rad) to double the natural occurrence of mutations. Of course, this risk is limited to individuals who are still capable of producing offspring. The concept of "genetically significant dose" has been developed to take into account that radiation exposure to older men and women is less likely to produce mutations.

The Greatest Radiation Risk to the Fetus: Teratogenesis

A serious radiation risk from diagnostic X-rays involves the possibility of severe mental retardation of an individual who received a large amount of radiation during the eighth to fifteenth week of gestation. This is the time when important cellular specialization is taking place in the brain of the fetus. For example, a barium enema study to a woman at this stage of pregnancy produces a probability of about 1:200 of severe mental retardation in the child. Of course, this effect can be caused by other physical, chemical, or genetic factors. Fortunately, this type of radiation exposure is relatively rare. No radiologist would intentionally do a radiation study of a woman at this stage of pregnancy that involved significant radiation to the fetus. If the woman did not inform the doctor of her pregnancy, the problem could occur.

How Is Radiation Measured?

Radiation is very easy to measure but difficult to measure accurately. Fortunately, in radiation protection, an accurate measurement is not needed. However, in the treatment of cancer with radiation the accuracy of delivered dose to the tumor should be better than 5%. For radiation workers or patients in diagnostic radiology, dose accuracy is seldom better than 20%, and an accuracy of 50% is generally acceptable. The dose to patients in diagnostic radiology is seldom measured. When they are measured, a large variation is found in doses for the same X-ray study.

A related problem is that conventional radiation quantities and units, as discussed earlier, are not adapted for easy communication with the patient. In the last section I suggest a new radiation unit that may help solve this problem.

Measuring Radiation by Ionization Methods

The oldest accurate technique for measuring radiation involves measuring the charge produced by the radiation (*2*). This can be done in two different ways. If the radiation is more or less constant, it is possible to measure the ionization current. This is a dose rate meter. The results will be given in R/hour or a similar unit. If the exposure is short, as in the case of an X-ray exposure, all of the ionization charge is collected and measured. This is called an "integrating dosimeter." A simple dosimeter of this type is a pocket or pen dosimeter. A capacitor is charged to about 400 volts. As the air in the chamber is ionized by the radiation, the ions produced are collected and discharge the capacitor. The charge loss on the capacitor during a given time is a measure of the radiation exposure. Most pen dosimeters include a simple electroscope to measure the remaining charge. They include a scale which indicates zero when fully charged. As it discharges, the scale shows the remaining voltage. The scale is calibrated to read directly in milliroentgen (mR).

Thermoluminescent Dosimetry: Casting a New Light on Radiation Dosimetry

Thermoluminescent dosimetry (TLD) was invented in 1954 by Professor Farrington Daniels of the University of Wisconsin-Madison. It was not brought to commercial applicability until the early 1960s. I was pleased to play a small role in this process. TLD is basically a simple technique that involves some complicated solid-state physics. I will not try to describe the details of the physics. TLD is based on the observation that many insulating crystals, when exposed to ionizing radiation, store some of absorbed energy, which is later released as light when the crystals are heated to a few hundred degrees celsius (well below the level of incandescence). The amount of light emitted can be measured and used to determine the amount of radiation that was absorbed. This phenomenon of emitting light when heated is called thermoluminescense. It is closely related to phosphorescence where light is emitted slowly at room temperature. Heating accelerates the emission of the stored energy. TLD crystals can store the energy for many years or even for centuries.

TLD is the most widely used technique to monitor workers at nuclear power plants. It is gradually replacing the older technique of film dosimetry to monitor workers in hospitals. Film dosimeters have advantages which will not be discussed here. TLD is in general more reliable and more accurate than film dosimetry. In addition, TLD has a much larger useful range. It can measure radiation from background levels to much greater than the lethal dose (5 to 10 Gy).

Did a Radiation Exposure Years Ago Cause Cancer? Use of PC Tables

There are two basic reasons for measuring radiation. First, radiation is measured to determine if the radiation exposure is in the "safe level" for the situation and if not, to correct the situation. A second reason is to establish evidence for the amount of radiation received in case a claim is later made that the individual's cancer was caused by unnecessary radiation. Since cancer is very common (about one out of four Americans will have cancer sometime during their lives), it is possible that some former radiation workers may feel that their cancer was caused by their occupational exposure. There are numerous law cases in the court system dealing with such situations. If the employer has good records establishing a low radiation exposure, the plaintiff often does not win the case.

In evaluating such cases, it is convenient to use PC tables. PC stands for "probability of causation," which in turn is an abbreviation of the phrase "the probability that a known radiation dose delivered at a particular age a known number of years ago will induce a cancer." That is, if a worker received 1 Sv of whole body radiation at age 20 and at age 30 developed cancer, what is the probability that this cancer was caused by the 1 Sv dose equivalent 10 years earlier? PC tables are based on experimental data from various sources, including the incidence of cancer in the approximately 80,000 survivors of the atomic bombs in Hiroshima and Nagasaki. There are no data for calculating risks at the low levels usually encountered in medical exposures. The PC for these doses are extrapolated from much higher exposures.

A New Unit of Radiation Risk for Patients and Workers

I wish to propose a new and improved patient radiation quantity called radiation risk and to define its basic unit to be year. Fractions of a year would naturally be expressed in days, weeks, or months as appropriate rather than as decimals. This unit is called background equivalent radiation time or BERT. (H. T. Richards, University of Wisconsin-Madison, suggested the name for the unit.)

Most patients are primarily concerned with the carcinogenic effect of X-rays. For medical X-rays this effect is roughly proportional to the energy imparted to the patient in mJ. Although the energy imparted is impossible to measure directly, for medical X-rays a good estimate of the energy imparted can be obtained from physical parameters measured during the exposure (*3–6*).

The quantity radiation risk is related to the carcinogenic risk from radiation exposure. This risk for a diagnostic X-ray is typically 10^{-5} to 10^{-4} per X-ray study. Patients generally have difficulty understanding such small risks. Thus I define radiation risk in terms of the equivalent risk from annual natural radiation in the United States. Let us assume that the probability of inducing cancer from a given X-ray study is Y, then the patient's radiation risk would be y/x year. Some typical values of radiation risk are given in Table 1.

This unit does not cover the relatively rare case of irradiation to the fetus during the eighth to fifteenth week. This risk will need a separate unit, perhaps defined in terms of the normal incidence of severe mental retardation in an unexposed population.

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